Development of Supersonic Retropropulsion for Future Mars Entry, Descent, and Landing Systems

8th International Planetary Probe Workshop

Short Course on Atmospheric Flight Systems Technologies

Portsmouth, Virginia, 4-5 June 2011

Karl Edquist (karl.t.edquist@nasa.gov), NASA Langley, Hampton, Virginia
SRP Element Lead
Exploration Technology Development & Demonstration Program
EDL Technology Development Project

Outline

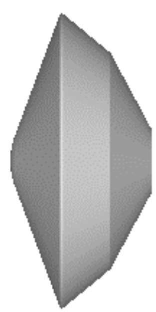
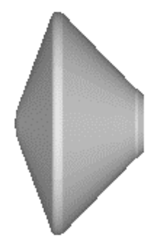
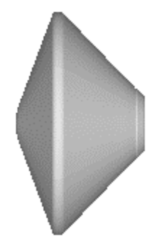
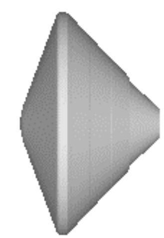
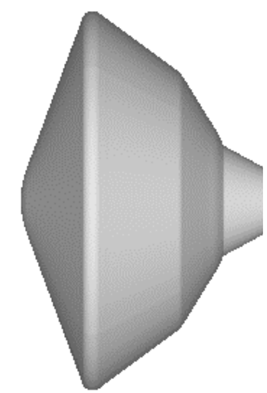
- Introduction to SRP
  - Motivation
  - Background
  - Technical Challenges

- SRP in NASA's EDL Technology Development Project
  - Objectives & Goals
  - Technical Highlights
  - Planning for 2012

Motivation for SRP

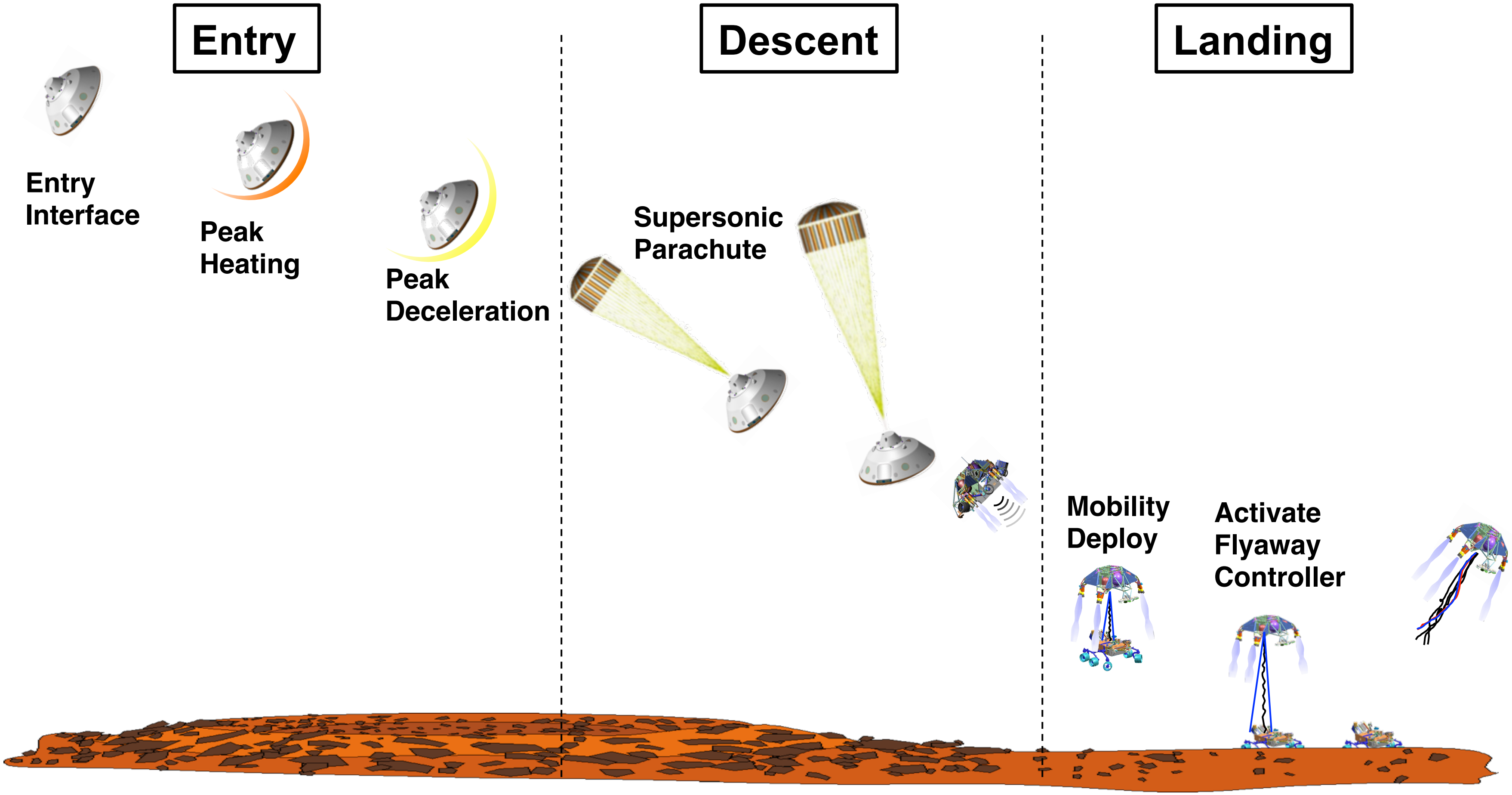
Successful U. S. Mars Entry Systems

- Evolutionary improvements to aeroshell + parachute systems since Viking
  - Nearing payload mass limit for Mars EDL → thin atmosphere
- Mars Science Laboratory will land almost 1 metric ton using the largest aeroshell & parachute, highest parachute Mach number, and highest L/D

	Viking 1 & 2 1976	Pathfinder 1996	MER A & B 2004	Phoenix 2007	MSL 2012
Aeroshell Shape (to scale)					
Aeroshell Diameter (m)	3.5	2.65	2.65	2.65	4.5
Entry System Mass (t)	0.99	0.58	0.83	0.60	3.38
Hypersonic L/D	0.18	0	0	0	0.24
Parachute Diameter (m)	16	12.5	14	11.7	21.5
Parachute Deployment Mach	1.1	1.57	1.77	1.65	2.1
Lander or Rover Mass (t)	0.244	0.092	0.173	0.167	0.95

MSL Entry, Descent, and Landing Sequence

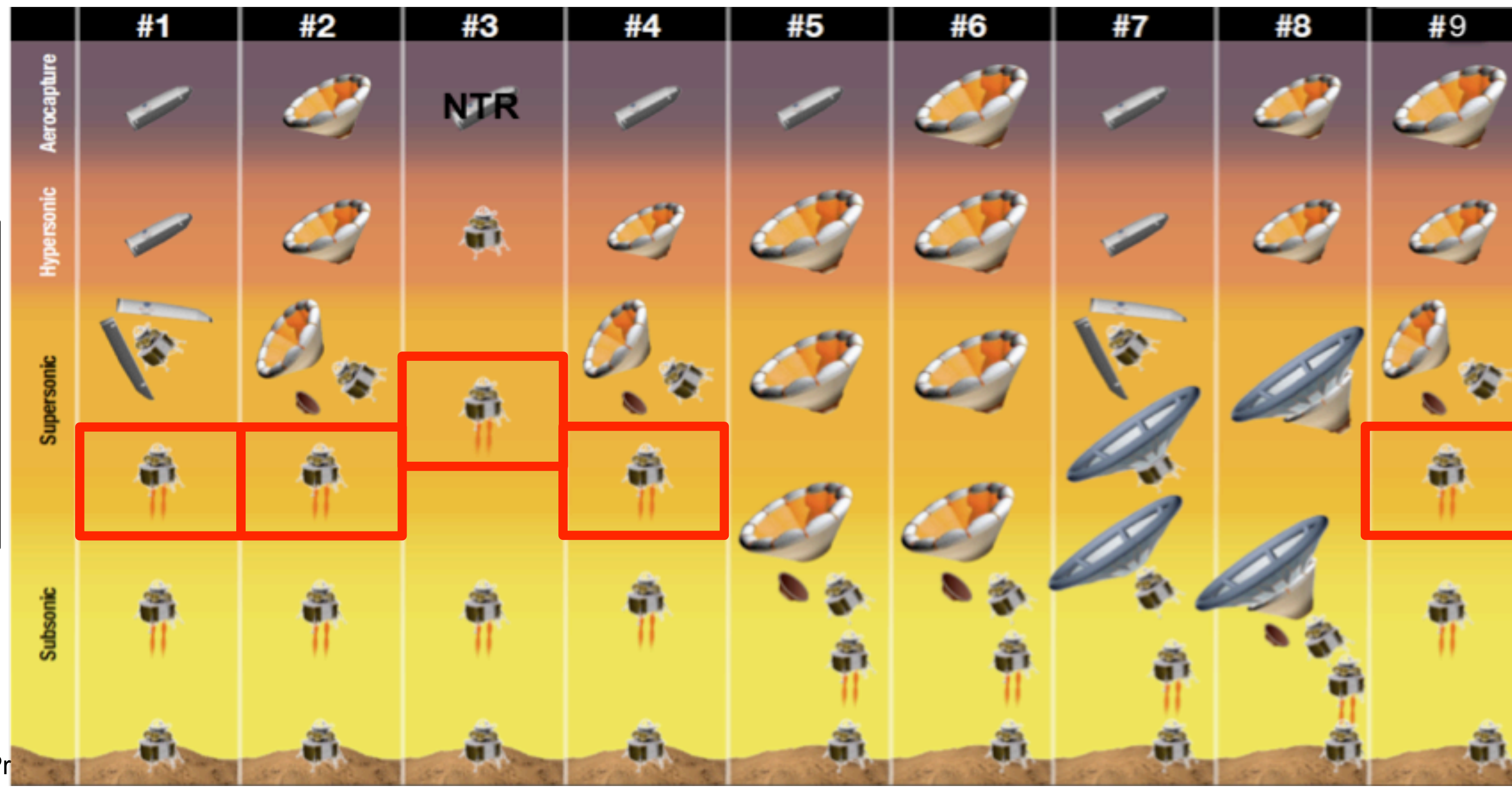
- How do we improve payload mass capability?
  - Increase drag area (IADs)
  - Increase drag or L/D (aerodynamically or propulsively)



EDL Systems Analysis (EDL-SA, 2009)

- 5 of 9 EDL-SA architectures require SRP for a 40 metric ton payload
  - 1.8 MN total thrust = 400,000 lbf, throttling
- Recommended technologies for NASA investment:
  - Deployable/inflatable aerodynamic decelerators (larger drag area)
  - More slender aeroshells (higher L/D)
  - Propulsive deceleration earlier in trajectory → **Supersonic Retropropulsion**

"Entry, Descent and Landing Systems Analysis Study: Phase 1 Report," NASA TM-2010-216720, July 2010



Motivation

- NASA's EDL technology roadmap calls for human exploration of Mars in the 2040s
  - "NASA DRAFT Entry, Descent, and Landing Roadmap, Technology Area 09," November 2010 (http://www.nasa.gov/offices/oct/home/roadmaps/index.html)
  - SRP is an enabling technology

Table 1. *Potential missions related to EDL technologies and capabilities*

Mission	Launch	Critical EDL Capabilities	Comments
Crewed Mars surface	2041	Mars large EDL: SRP, Mid L/D or large Deployable Decelerator	~30 metric tons lander

- Significant improvements are needed beyond MSL:
  - Order of magnitude increase in payload mass (10s of metric tons)
  - Four orders of magnitude improvement in landing accuracy (meters)
  - Higher landing elevation
- New EDL technologies are required!

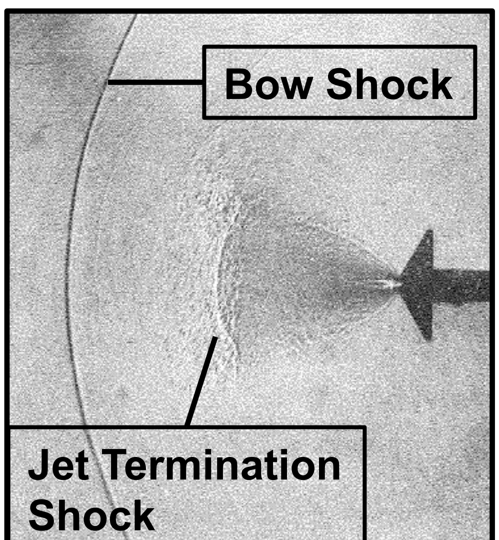
SRP Background

Historical SRP Studies

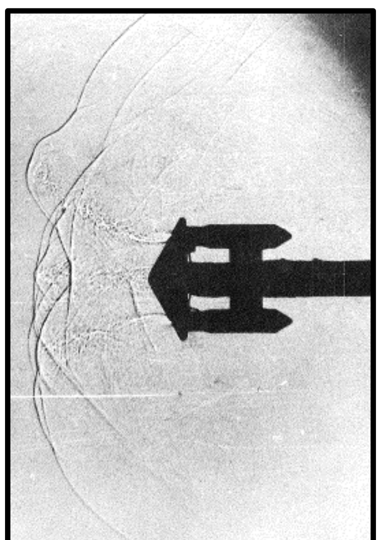
- SRP was first investigated in the 1960s
  - Focused on wind tunnel tests to examine the drag and aeroheating benefits of adding retrorockets to blunt shapes
  - Total drag, $C_{D,Total} = C_D$ (aerodynamic drag) + C_T (thrust / $q_\infty A_{ref}$)
- Supersonic parachute development eventually made SRP unnecessary for robotic Mars EDL (< 1 metric ton)

Jarvinen & Adams, NASA CR NAS 7-576

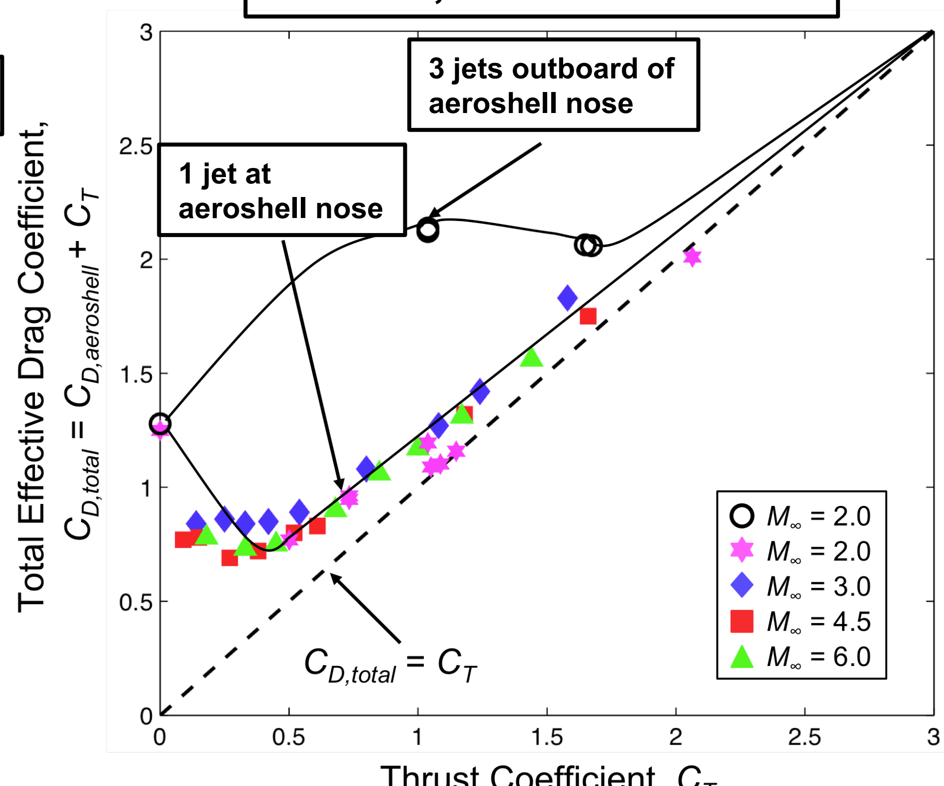
1 Jet, C_T = 6



3 Jets, C_T = 1



Korzun, AIAA 2010-5048



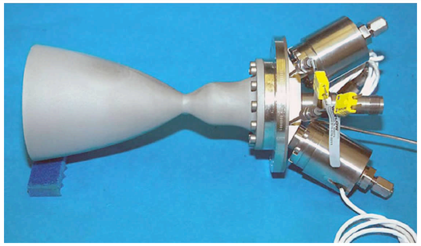
SRP Technology Readiness Level Current Status

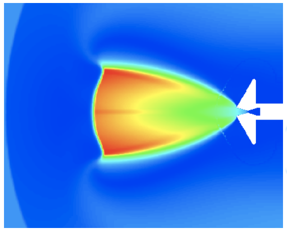
- SRP has not advanced much in the last ~40 years
  - Some wind tunnel testing & CFD, low-fidelity 3DOF trajectory simulations, small LOX/LCH4 engines
  - No SRP engine development, detailed systems analysis, flight testing
- We don't know what we don't know about SRP

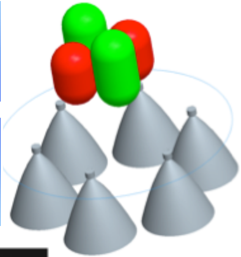
TRL	Definition	Phase
1	Basic principles observed and reported	Exploratory Research
2	***Technology concept and/or application formulated*** ✔	
3	Analytical and experimental critical function and/or characteristic proof-of-concept	
4	Component and/or breadboard validation in laboratory environment	Focused Technology
5	Component and/or breadboard validation in relevant environment	
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	

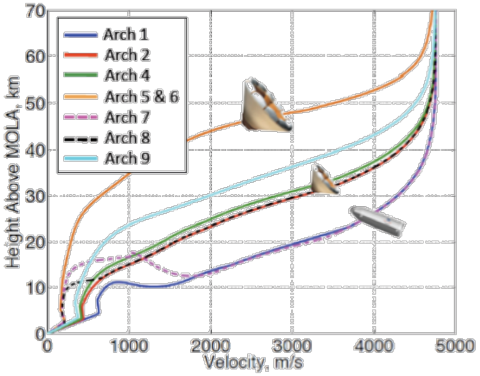
State of the Art and Needed Components

- Propulsion
  - SoA: 100-lbf LOX/LCH4 (no throttling), 28-klbf LOX/LH2 (20%)
  - Needed: O(10,000-lbf) deep throttling engines in supersonic flow
- Aerodynamics/Aerothermodynamics
  - SoA: Limited CFD analysis & assessment for SRP applications
  - Needed: CFD validated for 6DOF F&M predictions & aeroheating
- Guidance, Navigation & Control
  - SoA: Bank angle control using small RCS
  - Needed: SRP main engines and RCS control in complex flow
- Systems Analysis
  - SoA: Low-fidelity configurations, mass models, aero., etc.
  - Needed: High-fidelity models (CAD, CFD, thermal, etc.)
- Ground Testing
  - SoA: Cold-gas wind tunnel tests w/ pressure measurements
  - Needed: Real engines or simulated gases, realistic configurations, force & moment measurements
- Flight Testing
  - SoA: Not tested before
  - Needed: Earth atmosphere testing, Mars demonstration







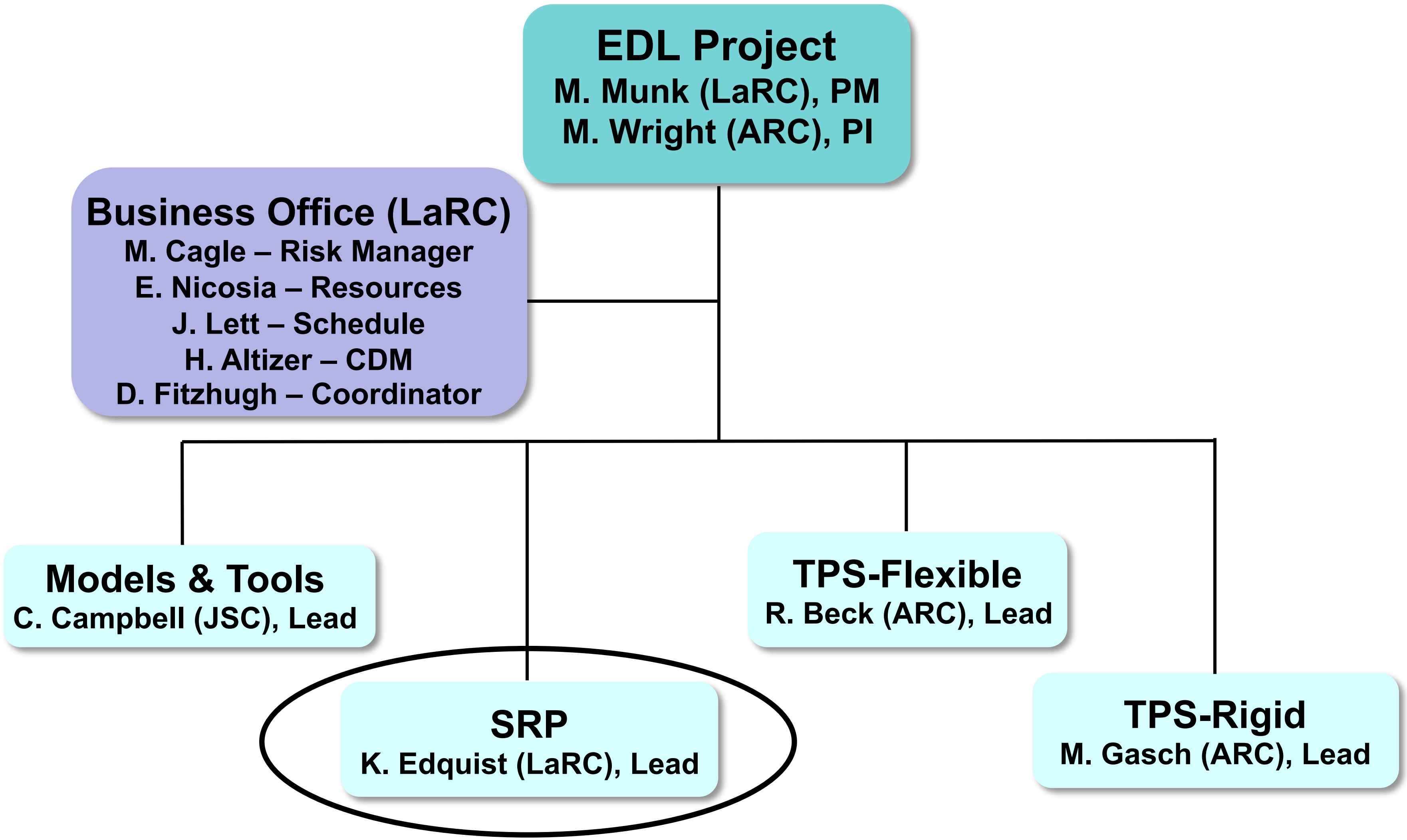


Overview of SRP in the NASA EDL-TDP

Overview of EDL Project, SRP Element

- The EDL Technology Development Project (EDL-TDP) started in 2009 and is the primary investor in SRP development at NASA
  - ARMD also invested in SRP in 2010/11, but will stop doing so in 2012
- Technical Objectives:
  - Develop a Technology Roadmap through TRL 5/6
  - Conduct wind tunnel tests to provide data for CFD validation
  - Demonstrate engine operation feasibility against supersonic flow
  - Begin assessing CFD codes for SRP applications
  - Develop pre-Phase A concepts for Earth-based flight testing
- Goals:
  - Achieve TRL 5/6 in late 2010s/early 2020s (depending on first use)
  - Complete first sounding rocket Earth flight test in mid-2010s
  - Reduce the risk of using SRP on future human-scale Mars EDL systems
- The EDL-TDP is closing out at the end of 2011
  - There is currently no guided funding for SRP in 2012

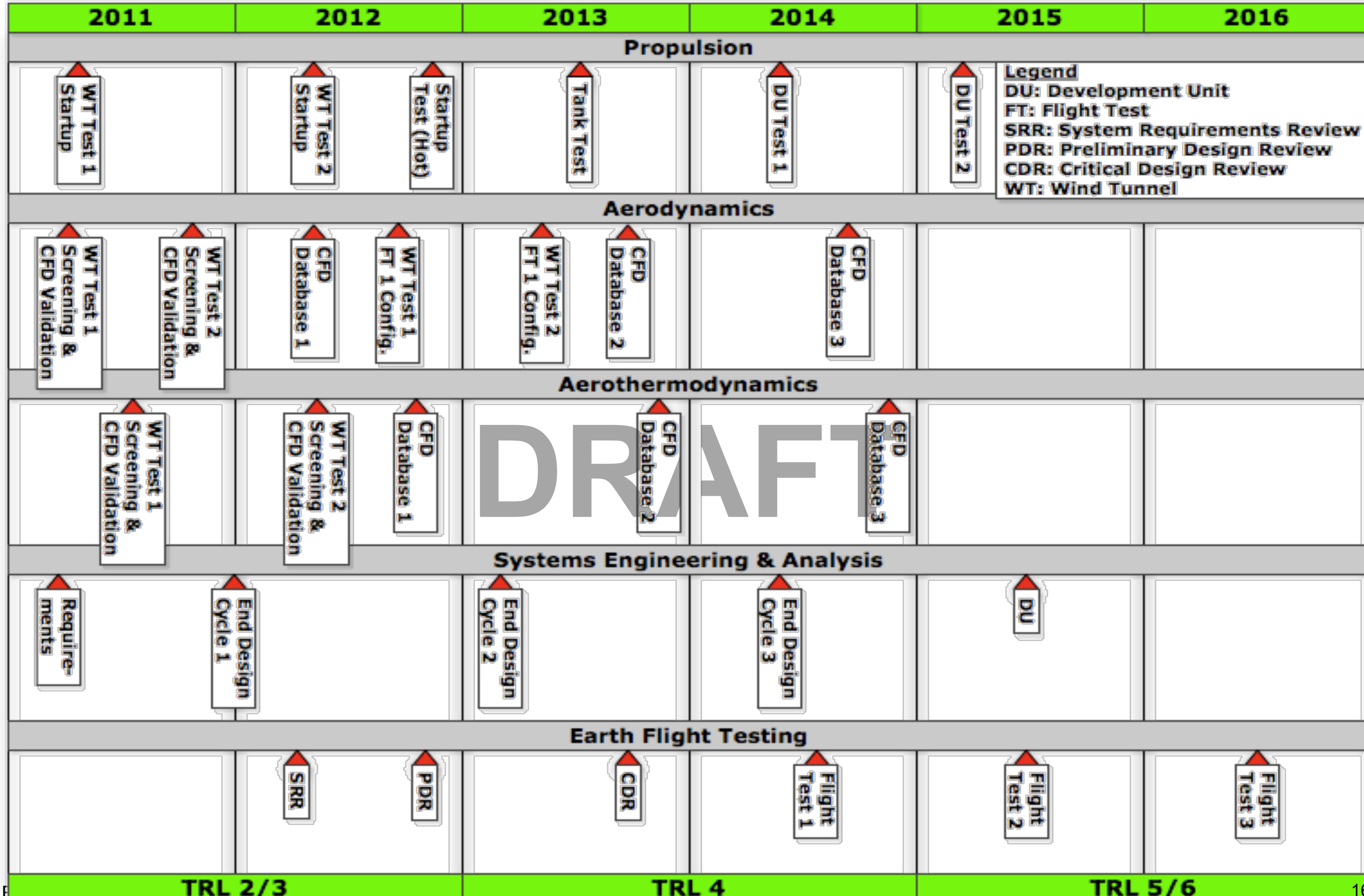
EDL Project Organization Chart



EDL-TDP SRP Team

- Ames Research Center:
  - Kerry Trumble
  - Emre Sozer
  - Ian Dupzyk
  - Noel Bakhtian (Stanford)
- Jet Propulsion Laboratory:
  - Ethan Post
  - Art Casillas
  - Rebekah Tanimoto
- Johnson Space Center:
  - Guy Schauerhamer
  - Bill Studak
  - Mike Tigges
- Glenn Research Center:
  - Tim Smith
  - Bill Marshall
- Langley Research Center:
  - Karl Edquist (Element Lead)
  - Scott Berry
  - Artem Dyakonov
  - Bil Kleb
  - Matt Rhode
  - Jan-Renee Carlson
  - Pieter Buning
  - Chris Laws
  - Jeremy Shidner
  - Joseph Smith
  - Ashley Korzun (Georgia Tech)
  - Chris Cordell (Georgia Tech)
  - Bill Oberkampf (Contractor)

SRP Roadmap (circa March 2010)



Recent and Future SRP References

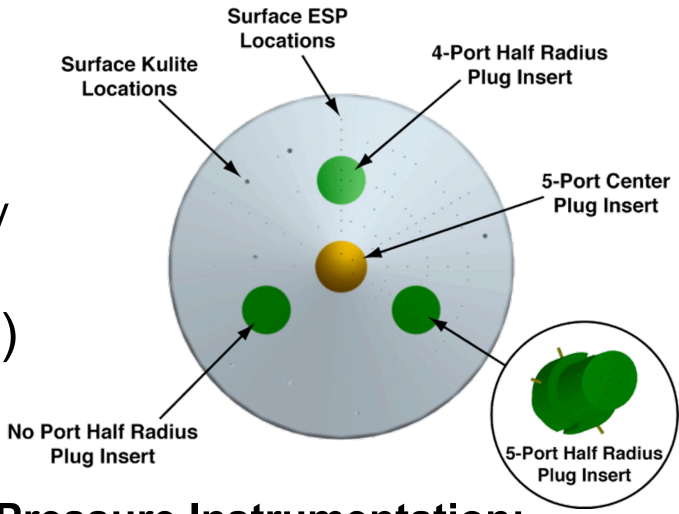
	Title or Topic	Lead Author	Conference/Journal
Wind Tunnel Testing	"Supersonic Retro-Propulsion Experimental Results"	S. Berry	AIAA Thermophysics Conference, Honolulu, HI, June 2011
	"Supersonic Retro-Propulsion Experimental Design for Computational Fluid Dynamics Model Validation"	S. Berry	IEEE Aerospace Conference, Big Sky, MT, March 2011
	ARC 9x7 Test Results	S. Berry	AIAA Thermophysics Conference, New Orleans, LA, June 2012.
	LaRC UPWT Test Uncertainty Analysis	M. Rhode	AIAA Ground Testing Conference, New Orleans, LA, June 2012.
CFD	"CFD Verification of Supersonic Retropropulsion for a Central and Peripheral Configuration"	C. Cordell	IEEE Aerospace Conference, Big Sky, MT, March 2011
	"Performance Characterization of Supersonic Retropropulsion for High-Mass Mars Entry Systems"	A. Korzun	Journal of Spacecraft and Rockets, Vol. 47, No. 5, pp. 836-848, Sept. - Oct. 2010
	"Supersonic Retropropulsion CFD Validation: Part I"	B. Kleb	AIAA Thermophysics Conference, Honolulu, HI, June 2011
	"Reynolds-Averaged Navier-Stokes Approach to Supersonic Retropropulsion Flowfields"	A. Korzun	AIAA Thermophysics Conference, Honolulu, HI, June 2011
	"Analysis of Inviscid Simulations for the Study of Supersonic Retropropulsion	N. Bakhtian	AIAA Thermophysics Conference, Honolulu, HI, June 2011
	"Ongoing Validation of Computational Fluid Dynamics for Supersonic Retro-Propulsion"	G. Schauerhamer	8th International Planetary Probe Workshop, Portsmouth, VA, June 2011
	"Analysis of Navier-Stokes Codes Applied to Supersonic Retro-Propulsion Wind Tunnel Test"	K. Trumble	AIAA Thermophysics Conference, Chicago, IL, June 2010
	"Maximizing Landable Mass Through Flow Control Via Supersonic Retropropulsion"	N. Bakhtian	8th International Planetary Probe Workshop, Portsmouth, VA, June 2011
	"Parametric Study of Peripheral Nozzle Configurations for Supersonic Retropropulsion"	N. Bakhtian	AIAA Aerospace Sciences Meeting, Orlando, FL, January 2010
	"Comparison of Inviscid and Viscous Aerodynamic Predictions of Supersonic Retropropulsion Flowfields"	A. Korzun	AIAA Thermophysics Conference, Chicago, IL, June 2010
	"An Initial Assessment of Navier-Stokes Codes Applied to Supersonic Retro-Propulsion"	K. Trumble	AIAA Thermophysics Conference, Chicago, IL, June 2010
	CFD Analysis of LaRC UPWT Test	G. Schauerhamer	AIAA Aerospace Sciences Meeting, Nashville, TN, January 2011
Systems Analysis	"Supersonic Retro-Propulsion Flight Test Concepts"	E. Post	8th International Planetary Probe Workshop, Portsmouth, VA, June 2011
	"Development of Supersonic Retro-Propulsion for Future Mars Entry, Descent, and Landing Systems"	K. Edquist	AIAA Thermophysics Conference, Chicago, IL, June 2010
	"Design Choice Considerations for Vehicles Utilizing Supersonic Retropropulsion"	A. Korzun	8th International Planetary Probe Workshop, Portsmouth, VA, June 2011
	Flight Test Concepts	TBD	AIAA Aerospace Sciences Meeting, Nashville, TN, January 2011
	"Design Choice Considerations for Vehicles Utilizing Supersonic Retropropulsion"	A. Korzun	AIAA Aerospace Sciences Meeting, Nashville, TN, January 2011

EDL-TDP Technical Highlights

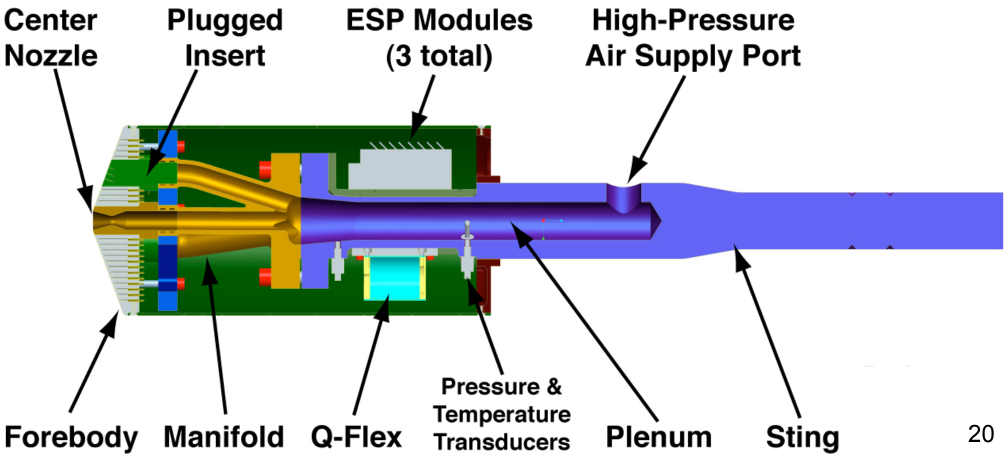
Wind Tunnel Testing

2010 LaRC 4’x4’ UPWT Test Summary

- Objective: Provide SRP data for CFD validation
  - CFD eventually will be used for full-scale aero/propulsive models in 6DOF trajectory simulations
  - Historical tests did not report on uncertainties or unsteady effects, and did not archive video
- LaRC UPWT test last July (co-funded w/ ARMD)
  - Generic 5” dia. model with 0, 1, 3, 4 cold-gas air nozzles
  - Mach = 2.6, 3.5, 4.6
  - AoA = 0, ±4, ±8, 12, 16, 20
  - Thrust Coefficients: C_T = 0.5 to 4+



Pressure Instrumentation:
- **118 Forebody Surface (ESP)**
- **7 Forebody Surface (Kulites)**
- **49 Aftbody Surface (ESP)**
- **4 Internal (Kulites)**

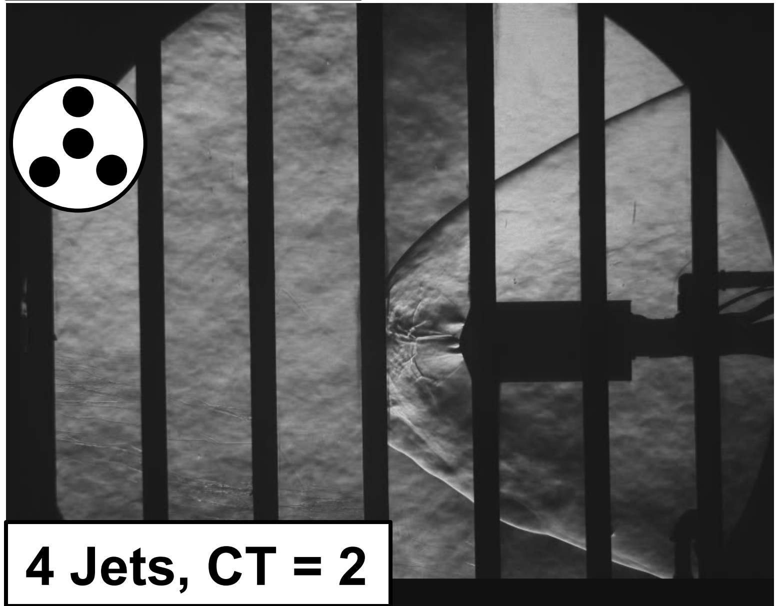


Effect of Jet Configuration
Mach = 4.6, AoA = 0

Baseline

1 Jet, CT = 2

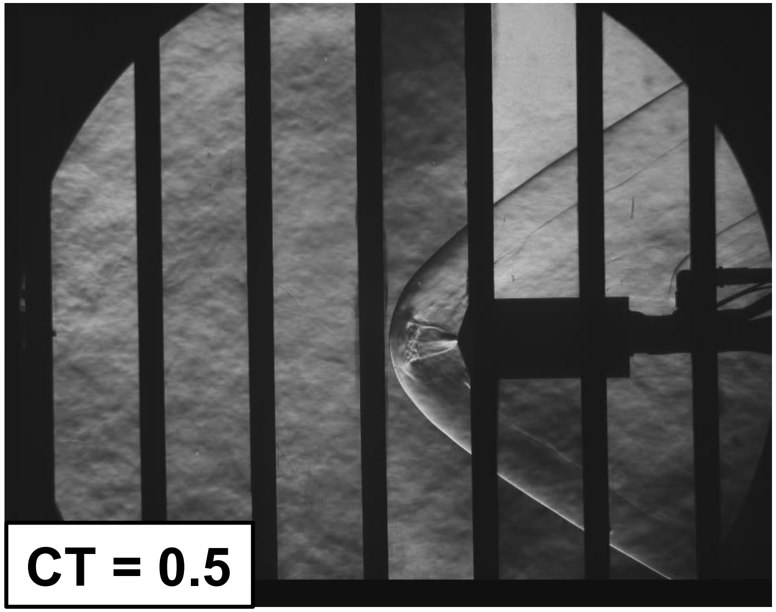
3 Jets, CT = 2

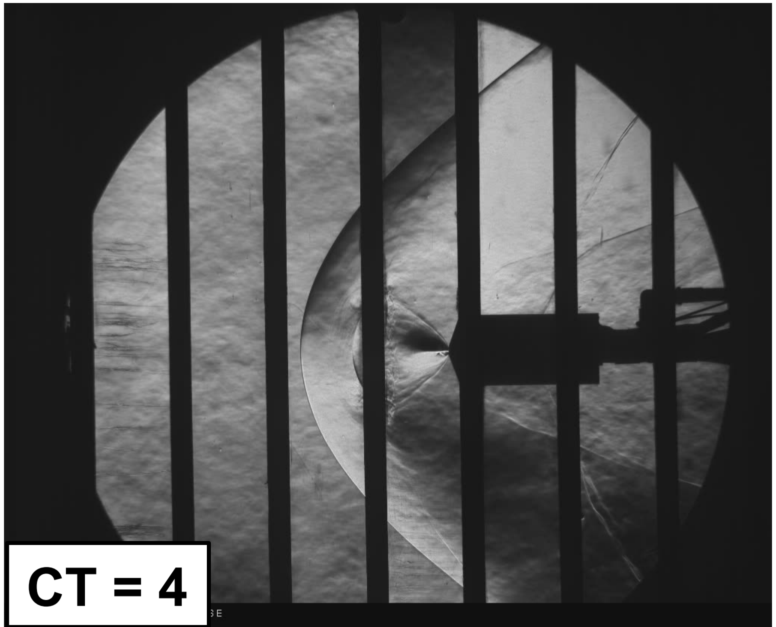


4 Jets, CT = 2

Effect of Thrust Coefficient
1 Jet, Mach = 2.4, AoA = 0

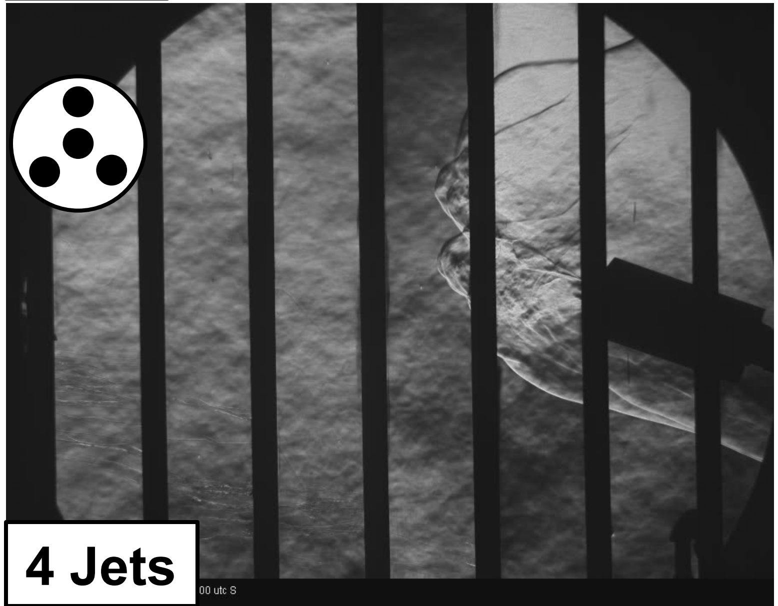
- Higher thrust pushes out the bow shock and creates a larger jet barrel due to a higher degree of jet under-expansion
  - Full-scale vehicle CTs > 10 are needed based on EDL-SA studies





Unsteady Flow at High AoA
Mach = 4.6, AoA = 20, CT = 2

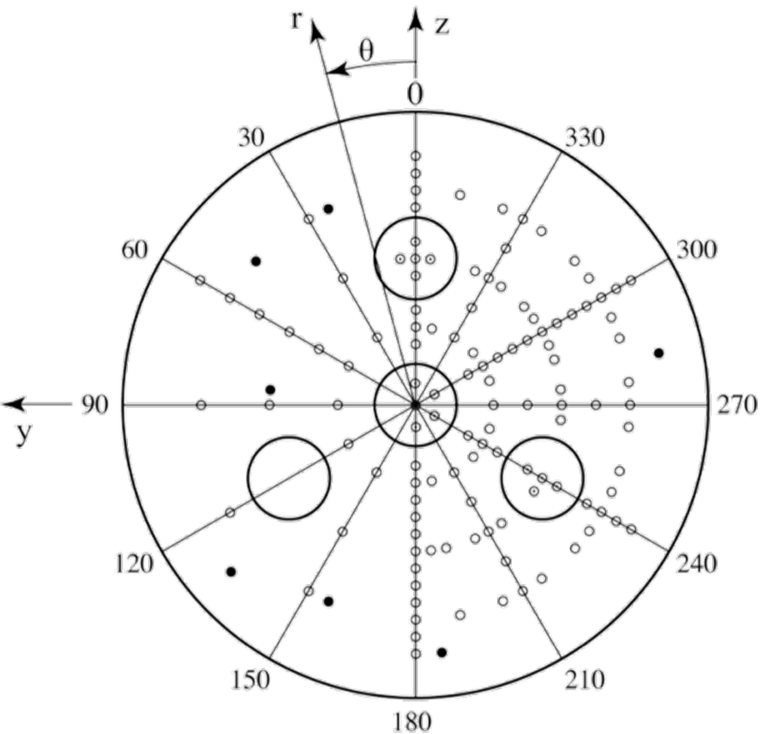
- The jet/freestream interactions become more complex and unsteady at high AoA
  - How could this affect full-scale vehicle aerodynamics and control?



LaRC 4'x4' Unitary Plan Wind Tunnel Test Uncertainty Analysis

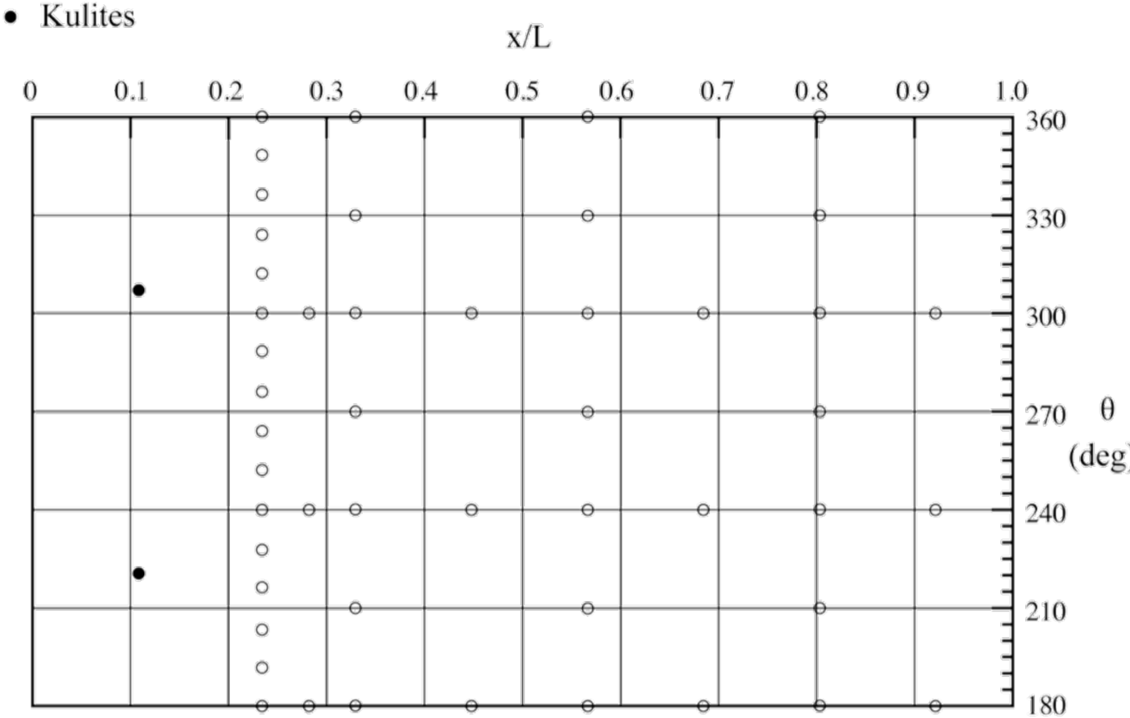
- Uncertainties were not addressed in historical wind tunnel tests
  - Total uncertainty = Random + flowfield non-uniformity + model/instrumentation
  - Method prescribed by Oberkampf → over 100,000 pressure port comparisons!
- First time this method will be used (to our knowledge) in a NASA wind tunnel

Forebody Pressure Ports



○ ESP Ports
● Kulites

Aftbody Pressure Ports



LaRC 4'x4' Unitary Plan Wind Tunnel Test Current Status

- Completed so far:
  - Wrote project report and two conference papers
  - Started uncertainty analysis

- To do:
  - Complete uncertainty analysis, report, paper
  - Complete high-frequency pressure analysis
  - Derive forces & moments from pressure data
  - Write NASA TM
  - Supply all necessary data to CFD team

- The LaRC model will be tested in the ARC 9x7 tunnel in August

Wind Tunnel Testing Future Planning

- By the end of 2011, we will have tested a single model in two different facilities
  - The roadmap calls for at least one cold-gas test per year
  - No definitive plans for testing next year

- Options for future testing:
  - Other generic configurations
    - Different no. and location of jets, model geometry, nozzle geometry, etc.
  - Different exhaust gases besides air
  - Aerothermal
  - Flight test or Mars configurations
  - Direct force & moment measurements
  - Independent throttling of nozzles
  - Other facilities

CFD Analysis

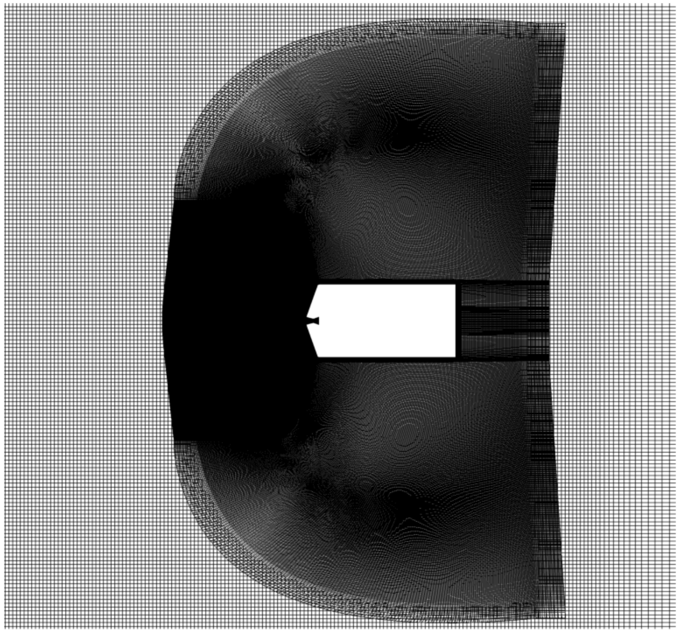
CFD Analysis

- CFD will eventually be used to predict full-scale vehicle SRP forces & moments and aeroheating environments
  - Complex turbulent & unsteady aero/propulsive interactions
  - Directly influences GN&C and TPS requirements
- Existing CFD codes are being compared against wind tunnel data
  - DPLR – K. Trumble, Structured, point-matched and overset grids
  - FUN3D – B. Kleb / J. Carlson, A. Korzun / C. Cordell, Unstructured grids
  - OVERFLOW – G. Schauerhamer, Structured, overset grids
  - US3D – E. Sozer, Unstructured-structured hybrid grids
  - Cart3D – N. Bakhtian (Stanford), Cut-cell Cartesian grids (inviscid)
- IPPW-8 Paper/Posters
  - "Ongoing Validation of Computational Fluid Dynamics for Supersonic Retro-Propulsion," G. Schauerhamer
  - "Design Choice Considerations for Vehicles Utilizing Supersonic Retropropulsion," A. Korzun
  - "Maximizing Landable Mass Through Flow Control Via Supersonic Retropropulsion," N. Bakhtian

CFD Analysis of LaRC UPWT Test

- Completed so far:
  - Completed run matrix of 6 cases
  - Investigated time step and grid spacing requirements
- To do:
  - Compare surface pressures to high-frequency data
  - Complete documentation (report, IPPW poster, AIAA papers)

OVERFLOW Grid



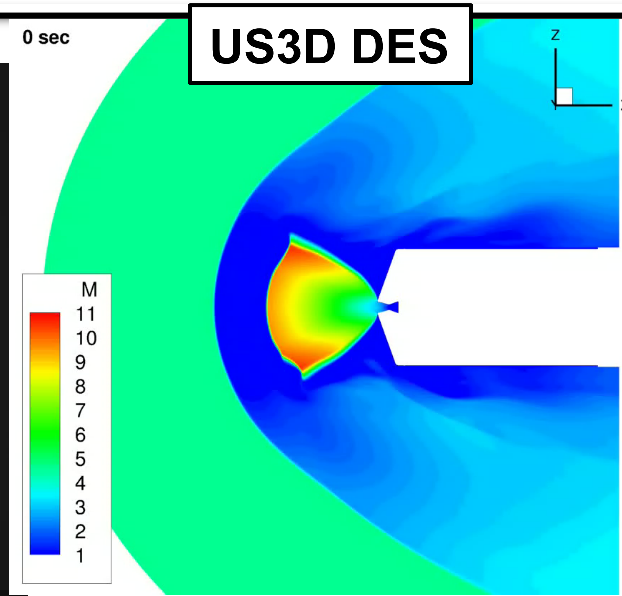
CFD Run Matrix for LaRC UPWT Test

Run	# Nozzles	M	CT	AoA	Roll
283	0	4.6	0	0, 12, 20	0
165	1	4.6	2	0, 12, 20	0
262	3	4.6	3	0, 12, 16	0
263	3	4.6	3	0, 12, 16	180
307	4	4.6	2	0, 12, 20	0
311	4	4.6	2	0, 12, 20	180

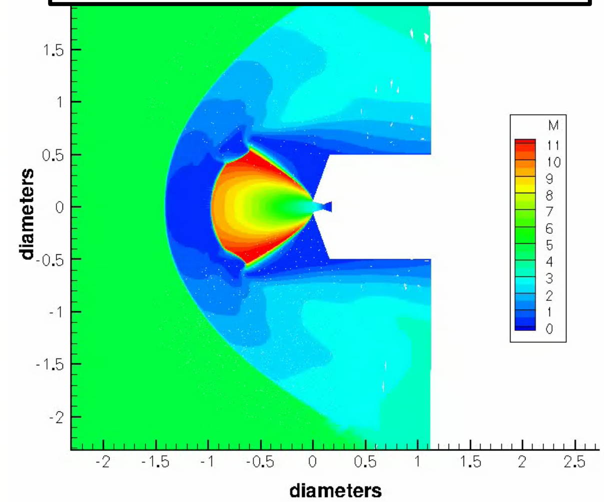
Run 165: 1 Jet, Mach=4.6, CT=2

Schlieren

US3D DES

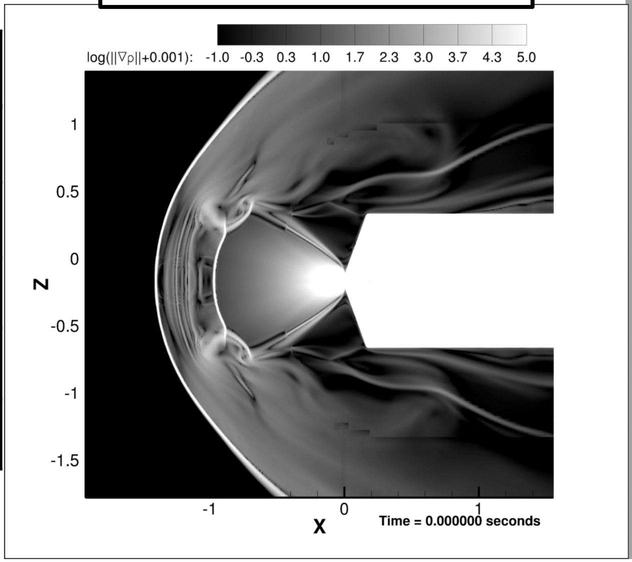


DPLR SST (17M cells)

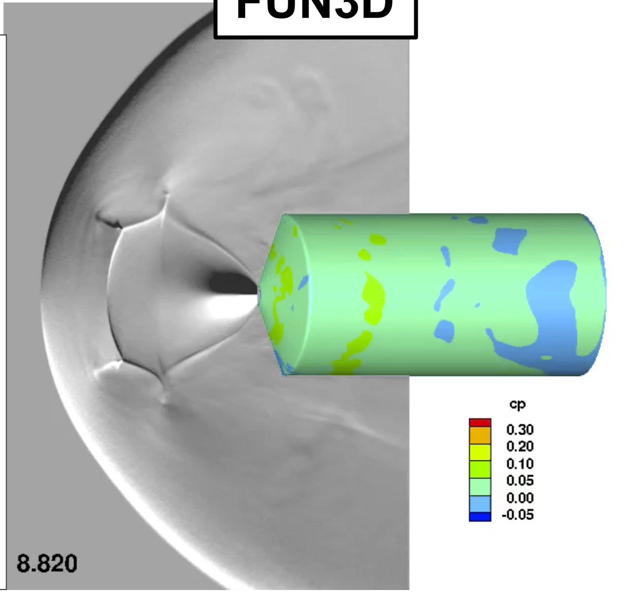


	Oscill. Freq (Hz)
Kulite Data	2.18
FUN3D	2.05
US3D	~1.7
OVERFLOW	2.05
DPLR	~1.7

OVERFLOW DES

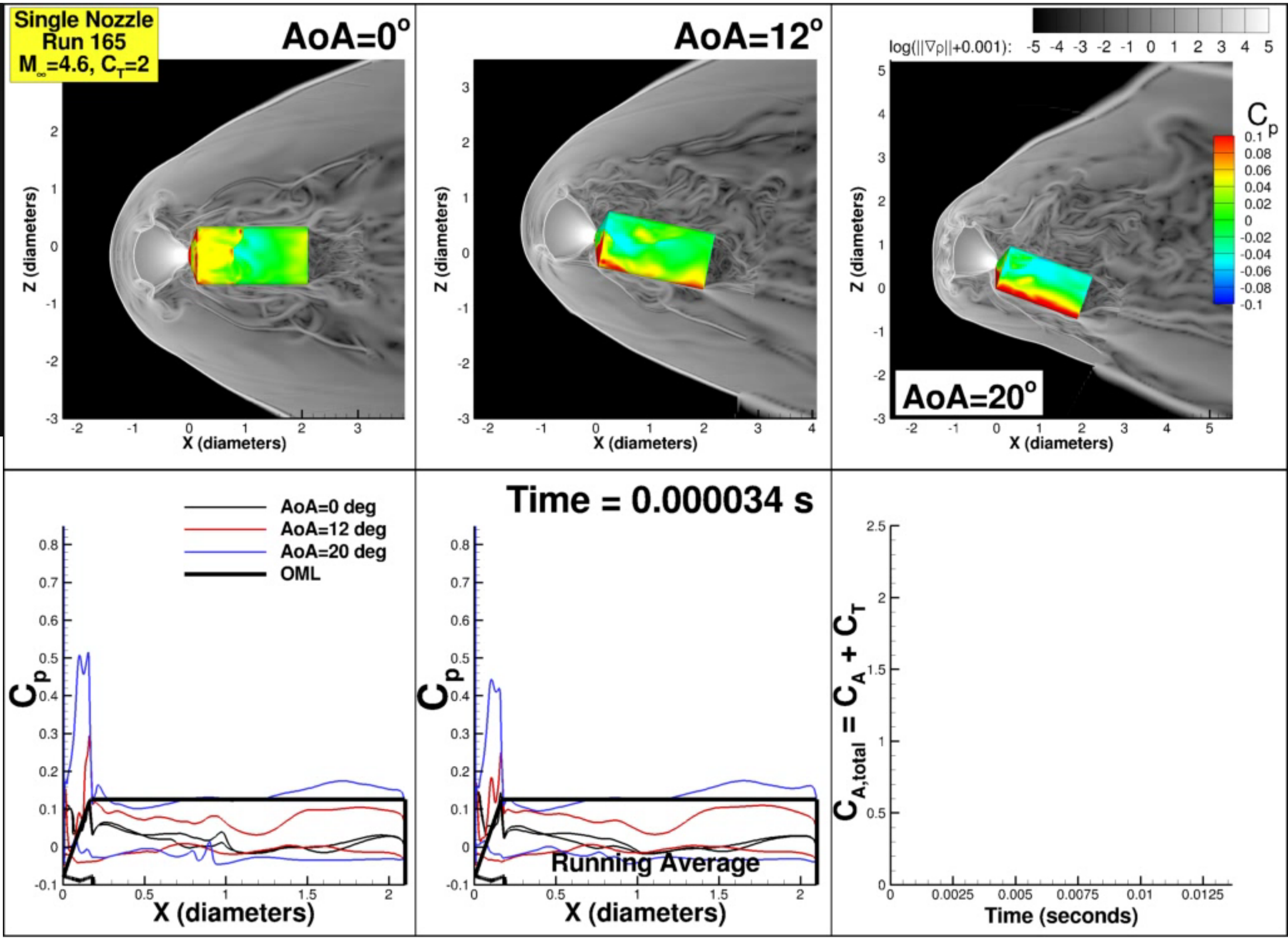


FUN3D



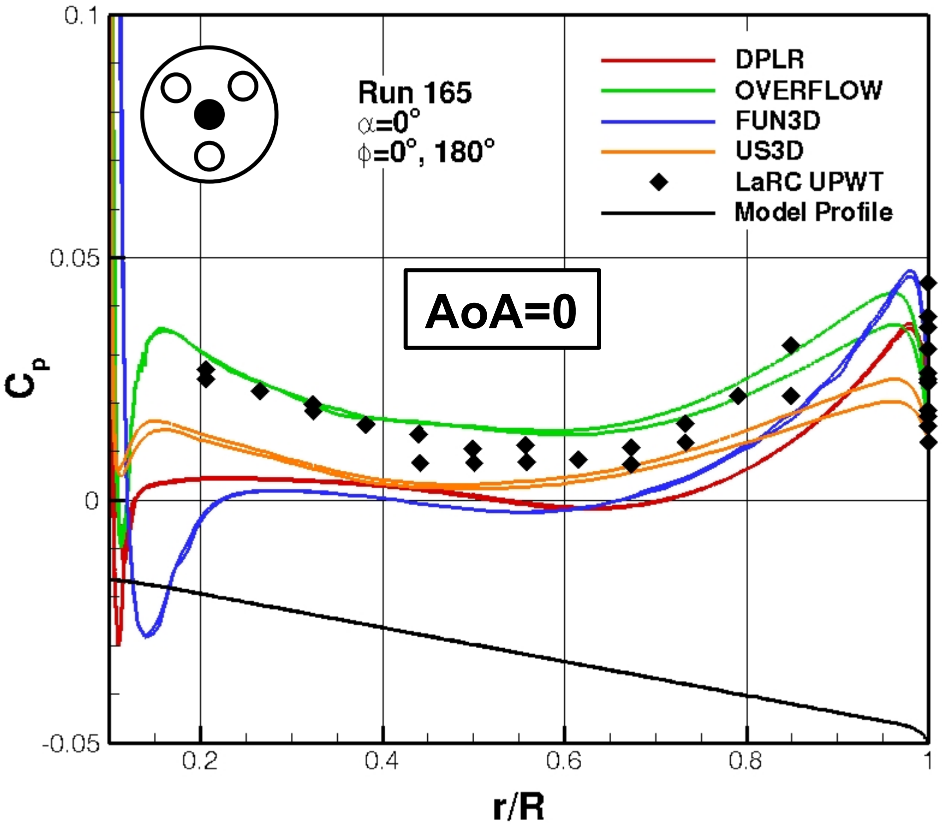
Run 165: 1 Jet, Mach=4.6, CT=2 OVERFLOW

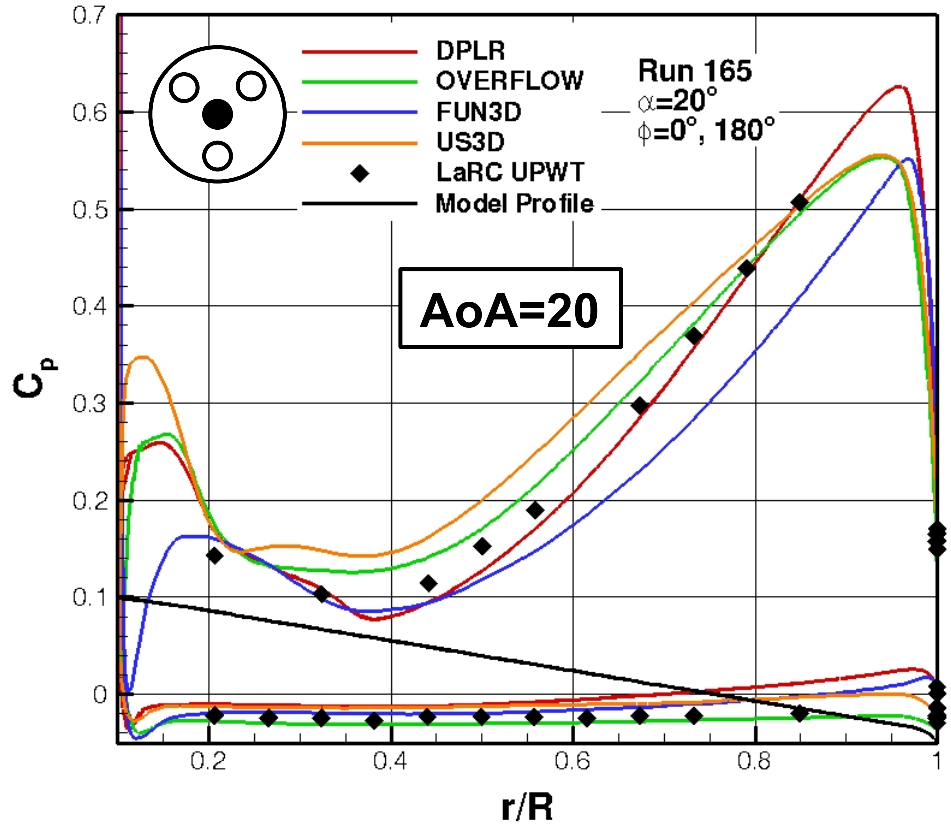
- Unsteady pressures are predicted at all AoAs
- Fluctuations in total drag are small compared to mean value



Run 165: 1 Jet, Mach=4.6, CT=2
CFD vs. Data, Forebody Pressure Coefficient

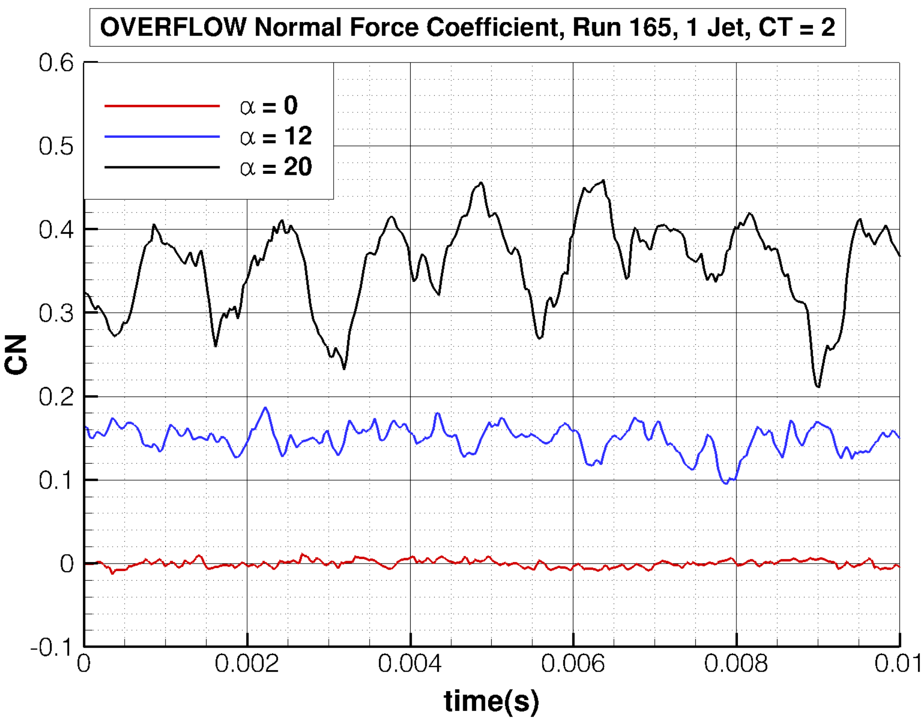
- Completed so far:
  – Compared CFD pressure to time-averaged data
- To do:
  – Add error bars to the data and RMS bars to the CFD

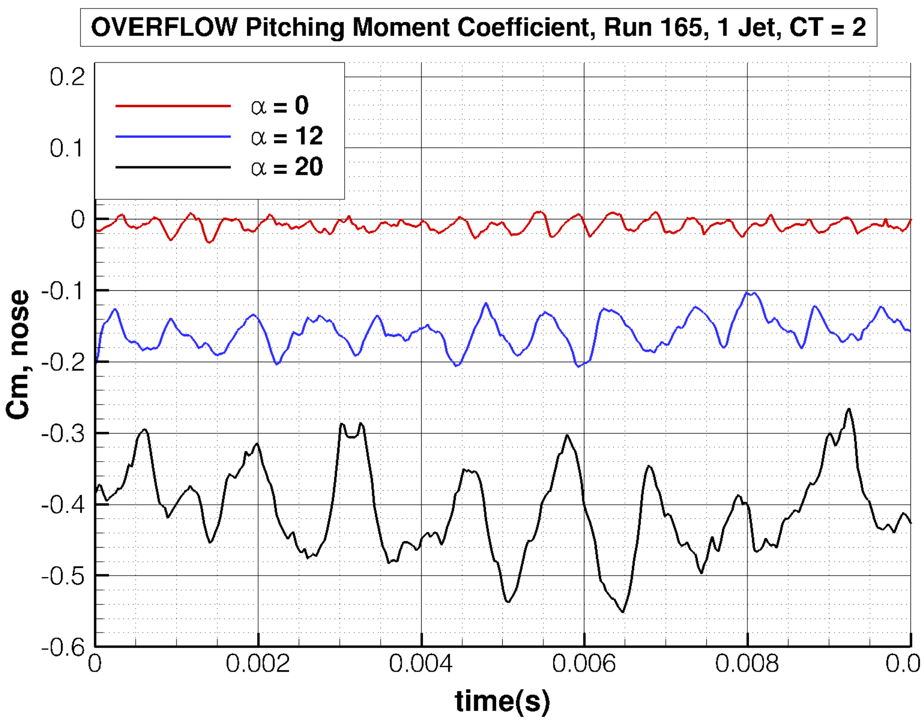




Run 165: 1 Jet, Mach=4.6, CT=2
OVERFLOW Aerodynamic Coefficients

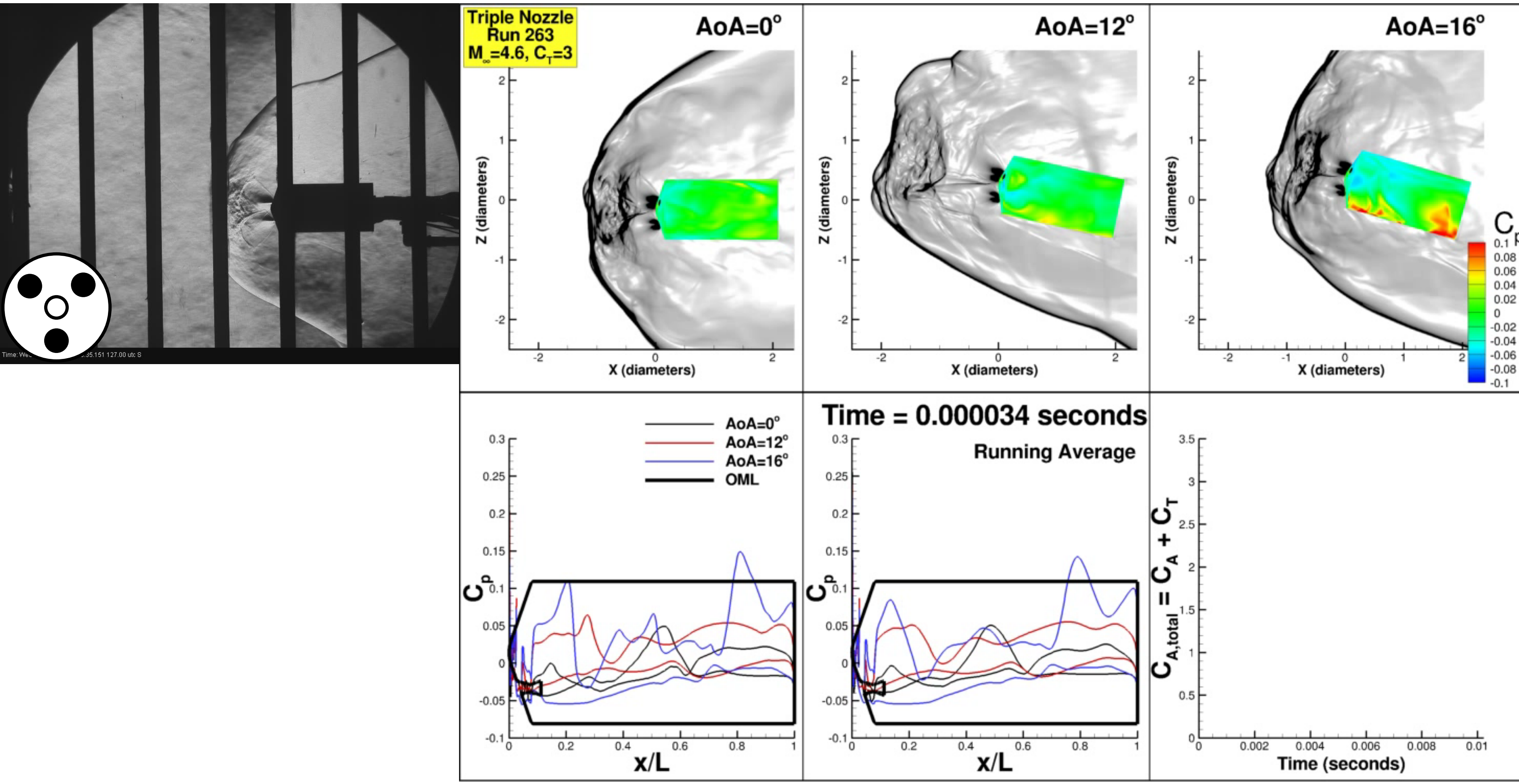
- Force & moment predictions will be needed for GN&C design
  - Unsteady CN & Cm will need to be handled by SRP main engines and/or RCS
- To do:
  - Run WT tests with direct F&M measurements
  - Validate CFD for F&M prediction





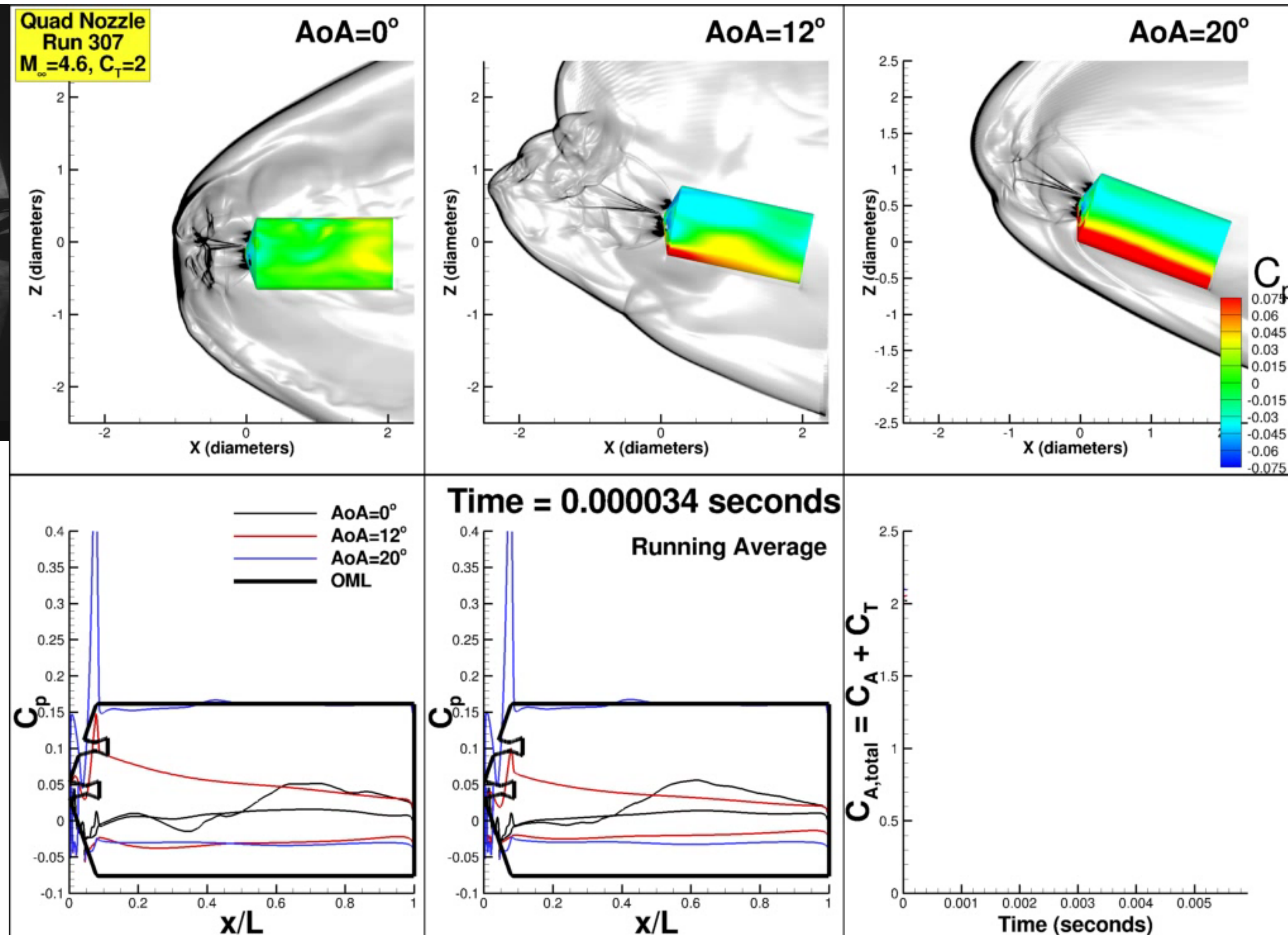
Run 263: 3 Jets, Mach=4.6, CT=3, Roll=180 OVERFLOW

- Total drag oscillations are more chaotic, but smaller in magnitude, compared to a single jet



Run 307: 4 Jets, Mach=4.6, CT=2, Roll=0 OVERFLOW

- Total drag oscillations are smaller in magnitude compared to a single jet and 3 jets



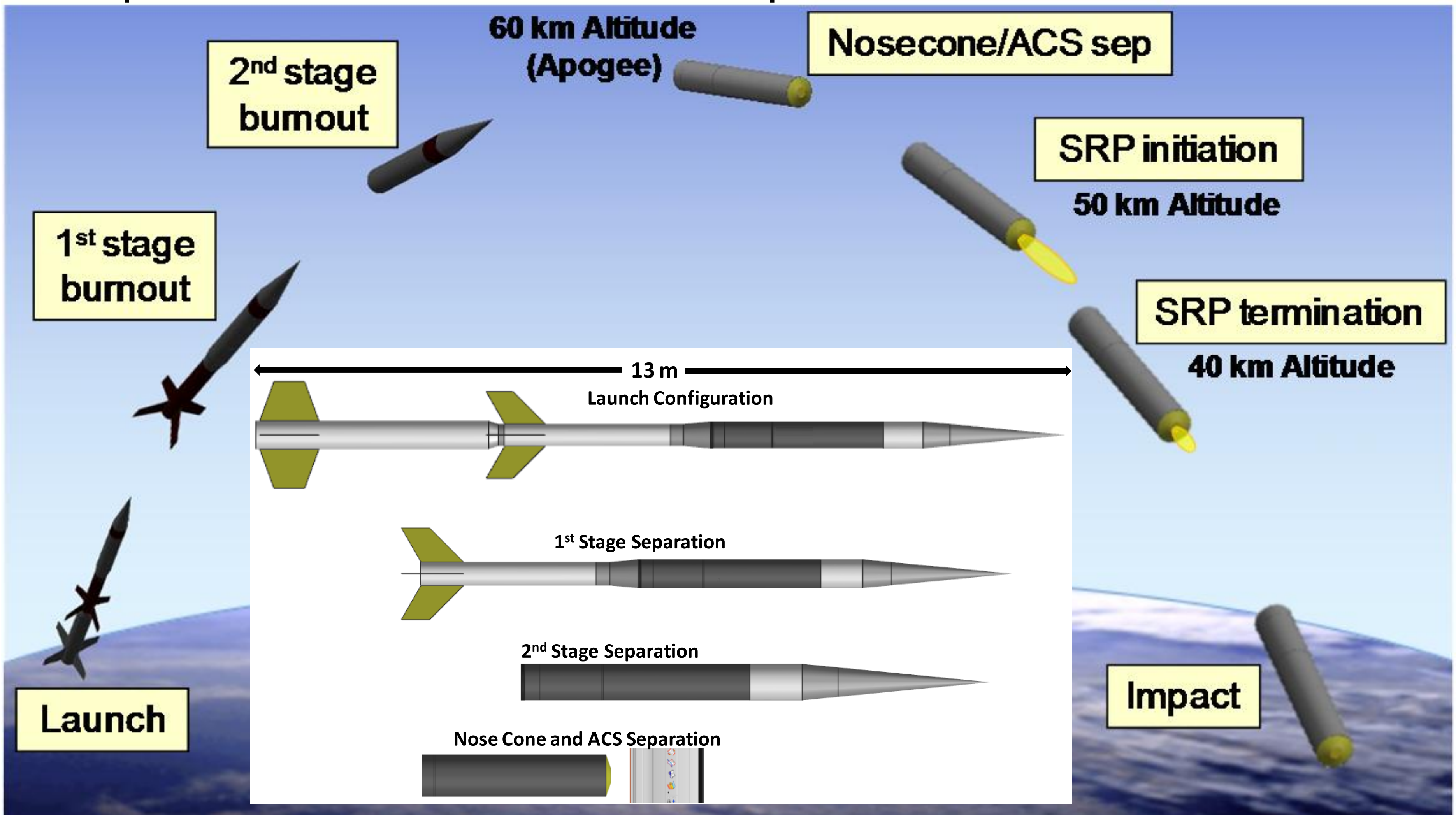
Flight Test Concepts

Introduction

- The SRP roadmap calls for a series of Earth-based flight tests to bring SRP to TRL 5/6
  - Can we successfully conduct a sub-scale test at Earth that confirms pre-flight performance predictions?
  - Can we reduce the risk of using SRP on Mars robotic and human missions?
- Test requirements, ConOps, and conceptual layouts have been completed for an initial sounding rocket flight test
  - Duration of test, Mach range, thrust coefficient, instrumentation
- IPPW-8 Paper
  - "Supersonic Retro-Propulsion Flight Test Concepts," E. Post

Flight Test 1 Draft Concept of Operations

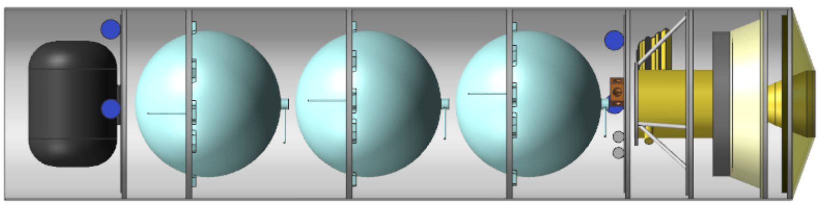
- Currently iterating with Wallops on sounding rocket capabilities and desired test sequence/conditions



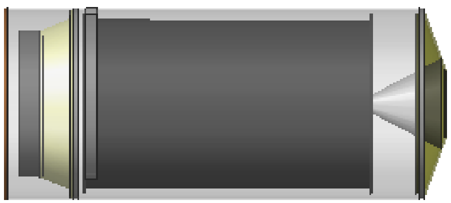
Flight Test 1 Concepts Overview

- Main discriminators are the engine/propellant type & volume
- Aerodynamic stability may be an issue for slender vehicles

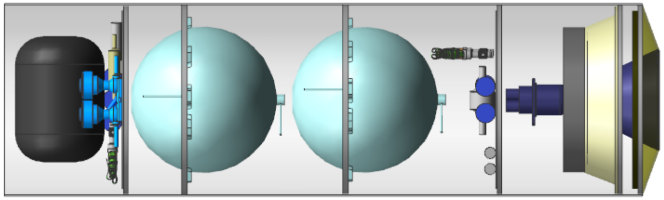
Monoprop (Pressure fed)



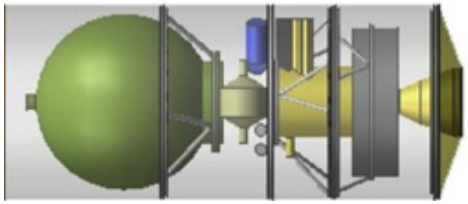
Solid



Biprop (pressure fed)



Monoprop (Blowdown)



Solid

Current Status

- Completed so far:
  - Completed draft requirements
  - Completed draft test objectives
  - Completed conceptual layouts with different engine options

- To do:
  - Rank candidate concepts and mature most promising
  - Refine Concept of Operations
  - Iterate on desired requirements with sounding rocket capabilities (Wallops) and test phase simulations (EDL-TDP team)
  - Investigate possible funding paths for test proposal

Summary

2011/2012 Plans

- ARC 9x7 SWT Testing
  - Complete test documentation (report, conferences papers, NASA TM?)
- Glenn 10x10 SWT Testing
  - Real engine testing at supersonic conditions
  - Modify tunnel to handle propellants and water cooling
  - Conduct sea-level testing
- CFD Analysis
  - Run post-test matrix from ARC 9x7 SWT test
  - Pre-test support of Glenn 10x10 SWT engine test
  - Run Mars flight cases
- Systems Analysis
  - Mature downselected flight test concept(s) and prepare proposals

- Investigate and pursue potential funding avenues

Wrapup

- SRP is a potentially enabling technology for future human-scale Mars EDL systems
  - Deep-throttling engines O(100) klbf thrust capable of operating against supersonic flow are needed
  - Computational models for aero/propulsion interactions need to be validated → initial results are promising
  - Earth-based testing is needed to reach TRL 5/6
- NASA's EDL-TDP and ARMD SRP teams have made excellent progress
- High-priority SRP tasks must maintain momentum into 2012
  - Wind tunnel testing
  - Engine testing
  - CFD analysis & development
  - Flight test planning
- Proposal and funding avenues are being explored

Acknowledgment

- The SRP team wishes to acknowledge the support of the Exploration Technology Development and Demonstration (ETDD) Program, managed at NASA-Glenn Research Center. The work documented herein was performed as part of ETDD's Entry, Descent, and Landing (EDL) Technology Development Project, which is managed at NASA-Langley Research Center and supported by NASA-Ames Research Center, NASA-Johnson Space Center, and the Jet Propulsion Laboratory.